Sunspot penumbrae: observations and numerical modeling

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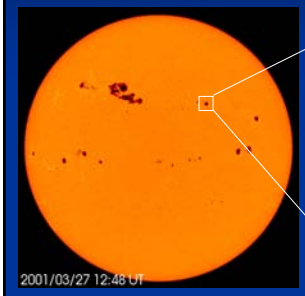
Overview

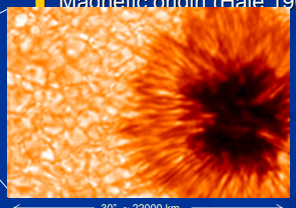
- Introduction
- Observations:
  - Spectropolarimetry in two dimensions with high spatial resolution
  - Results
- Numerical Modeling
  - Geometry of the model
  - Synthetic profiles
- Summary

Sunspots



MDI (SoHO)

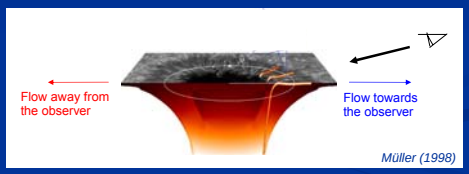
- Magnetic origin (Hale 1908)



VTT, 2003

Penumbra: Evershed effect

Eversheld (1909): displacements in wavelength and asymmetries in spectral line profiles in the penumbra



Müller (1998)

Blueshifted spectral lines in centre side penumbra

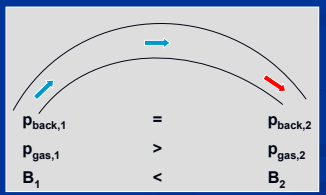
Redshifted spectral lines in limb side penumbra

→ **Radial outflow of the material**

Evershed effect: models

Siphon flow

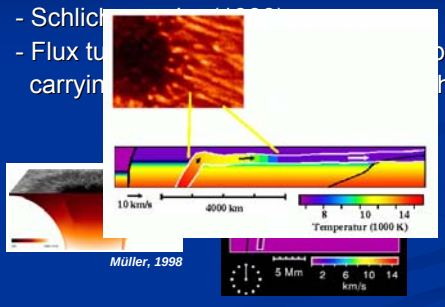
- Meyer & Schmidt (1968)
- Montesinos & Thomas (1997)
- Thin arched tube with footpoints at different gas pressure



Evershed effect: models

Moving flux tube

- Schlich
- Flux tu penumbra
  carryin hotosphere

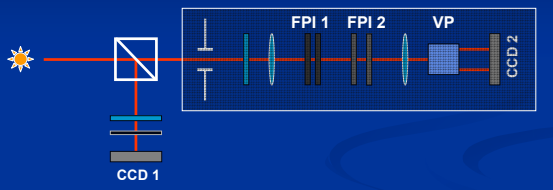


Müller, 1998

Observations

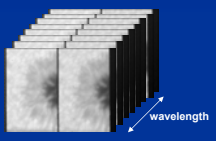
VTT, Tenerife

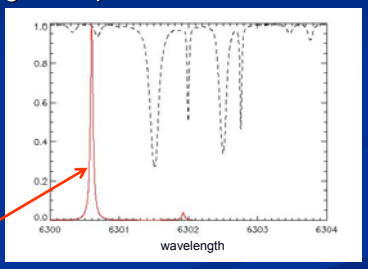
Göttingen FPI



Observations

Circularly polarised light components

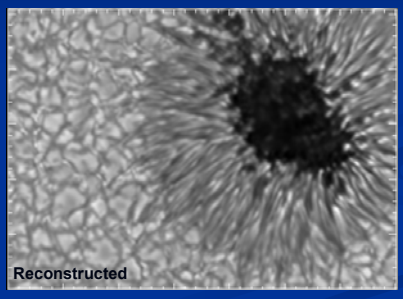




Airy function of the FPI

Image reconstruction

Speckle reconstruction: *Weigelt (1977), von der Lühe (1984)*

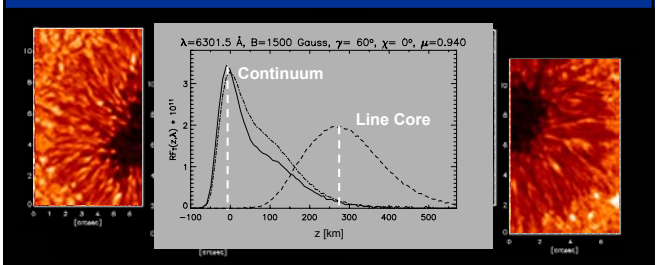


Broad-band data (~150 frames, short exp. time)

Observational results

I. Analysis of intensity maps (Fe I 6301.5Å)

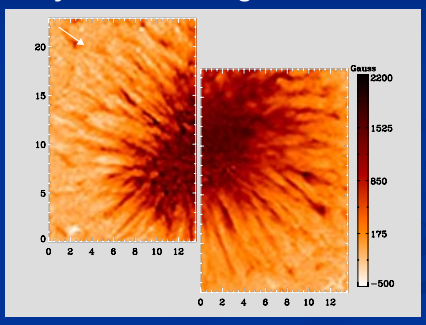
Continuum Line Core



Range of formation: from the solar surface (τ_{5000}=1) up to 300 km

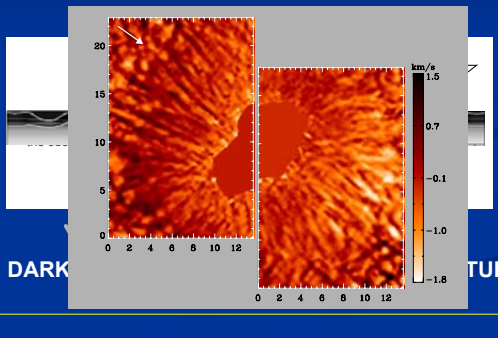
Observational results

II. Analysis of LOS magnetic field:



Observational results

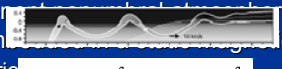
III. Analysis of LOS velocities: Fe I 6301.5Å



DARK TURES

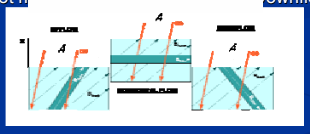
Numerical modeling

- Motivation: observations and MHD models
- Two-compon[illegible]e:
  flux tube em[illegible]c 'background'
- Three scenario[illegible]



$$p_{tube} + \frac{B_{tube}^2}{8\pi} = p_{back} + \frac{B_{back}^2}{8\pi}$$

Upflow of hot m[illegible]ownflow of cold matter



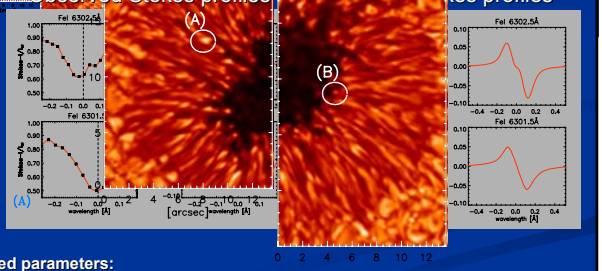
- 1D radiative transfer problem is solved along two rays

$$I_{syn} = f I_{ray1} + (1-f) I_{ray2}$$

Synthetic profiles

grain in mid-penumbra:

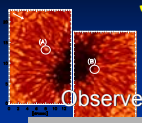
Observed Stokes profiles [illegible] kes profiles



Used parameters:

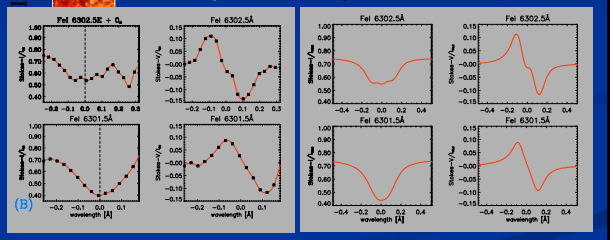
$T_{tube} > T_{back}$ $|v_{tube}| \sim 10$ km/s $|B_{init}| \sim 2500$ G $R_{tube} \sim 50$ km $\theta \sim 20°$

Synthetic profiles



B) Penumbral grain close to the umbra

Observed Stokes profiles Synthetic Stokes profiles



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Summary

- 2D spectropolarimetry + high spatial resolution provide much information about the fine structure of the sunspot penumbra:
  - On small scales (<0".4), the structure varies substantially with height, filaments loose identity between 0 and 300 km
  - The Evershed flow is carried by bright filaments in the centre-side penumbra and by the dark filaments in the limb-side penumbra
  - The uncombed structure of the magnetic field is confirmed
  - Results compatible with the picture of low lying flow channels, emerging and diving down into the sub-photospheric layers (sea serpent)

Summary

- Synthesis of Stokes profiles is needed to understand the observed asymmetries:
  - First synthesis from forward modeling of a two-component penumbral model can reproduce observed profiles in given structures